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We propose that the knee in the cosmic ray spectrum at energies $E \gtrsim 10^{15.5}$ eV is due to "new physics", namely to a channel in the high energy ($\gtrsim$ TeV in the CM) proton interactions hitherto unaccounted for in estimating the energies of the air shower cosmic rays. The new interaction transfers part of the primary particle's energy to modes which do not trigger the experimental arragement (neutrinos, lightest supersymmetric particle, gravitons) thus underestimating its true energy. We show that this underestimate leads naturally to the observed break (the "knee") in the *inferred* cosmic ray spectrum. The suggestion we advance fits nicely to current theoretical extensions of the Standard Model (supersymmetry, technicolor, low scale gravity) where new physics at the TeV scale manifests with the distinct signature of missing energy. We present a simple model where the new physics proceeds via gluon fusion and assuming a single power law for the galactic ($E \lesssim 10^{18.5}$ eV) cosmic ray spectrum, we produce a good fit to the data in the $10^{14} - 10^{18.5}$ eV range. Our proposal should be testable in laboratory experiments (LHC) in the near future and, should it proven correct, it would signal besides the presence of new physics in high energy interactions, a drastically different interpretation of the sources and acceleration of cosmic rays.

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The origin of cosmic rays is a subject which, despite the observational and theoretical progress made since their discovery has not been settled as yet. The reason can be traced to the breadth of their spectrum which extends over 11 orders of magnitude to $\gtrsim 10^{20}$ eV (see e.g. [1] for a recent review) and the fact that by virtue of their diffusion through the galaxy most information concerning their sources is practically lost. Thus, to zeroth order, especially at higher energies ($> 10^{12}$ eV) at which cosmic ray composition measurements are difficult, the sole source of clues about the cosmic ray origin and acceleration is their over all spectrum.

The cosmic ray spectrum consists, roughly speaking, of three distinct sections, each of power law form, $E^{-\gamma}$ in the particle energy E, but with different values for the index γ: In the range $10^9 - 10^{15.5}$ eV the index $\gamma \simeq 2.75$. Above this energy (the "knee"), the spectrum steepens to a power law of $\gamma \simeq 3$ which extends to $\sim 10^{18}$ eV, with some evidence for a further steepening in the spectrum indicating a possible cut-off at $E \simeq 10^{18.5}$ eV [2]. This steepening is reversed at slightly larger energies (at the "ankle") with the spectrum flattening to $\gamma \sim 2 - 2.5$ and extending to $E \simeq 10^{20.5}$ eV, at which point the existing statistics are too poor to provide a well defined flux measurement.

Considering that cosmic rays propagate in the galaxy by diffusion through the tangled interstellar magnetic field, one can argue convincingly that particles with gyroradii larger than the galactic scale height (~ 1 kpc) ought to be extragalactic. Given that the gyroradius of a proton of energy $E(eV)$ is $R_g \sim 1$kpc E_{18}/B_{-6} (where $E_{18} = E(\mathrm{eV})/10^{18}$ and B_{-6} is the galactic magnetic field in μG), it is expected that protons of energy $E \gtrsim 10^{18.5}$ would escape freely from the galaxy. This notion is in agreement with the indication of an additional steepening or a potential cut-off in the spectrum at $E \gtrsim 10^{18}$ eV, with the subsequent flattening at higher energies being naturally interpreted as due to a "harder" extragalactic component.

This latter extragalactic component, which includes several events above 10^{20} eV, has caught recently the attention of the community: It is well known [3] that protons of energies $\gtrsim 10^{19.5}$ eV suffer catastrophic photopion production losses on the Cosmic Microwave Background (CMB). If this extragalactic component premeates uniformly all space, as it was thought to be the case, this process should then lead to a cut-off (the so-called GZK cut-off) rather than an excess flux above this energy. The potential identification of the source of this component with either gamma ray bursts within 100 Mpc [4], a novel, neutral hadron immune to the photopion losses [5], or the decay of heavier Big–Bang relics [6] has provided the impetus for a recent flare of activity regarding the origin of this specific part of the cosmic ray spectrum (see [7] for a review).

However, it is not only this highest energy regime which defies our understanding of the cosmic ray spectrum origin. The spectrum at energies $E \lesssim 10^{18.5}$ eV, thought to be galactic (see however [8]) and presumably easier to comprehend, challenges on its own right, arguably more severely than the extragalactic component, our understanding of its origin. Though counter intuitive at first glance, it is a simple matter to assess the correctness of this statement (see [9]): It is easy to obtain a "flattening" of the (any) spectrum by combining two independent components, since the harder one will always dominate at sufficiently high energies. This appears to be the case with the cosmic ray spectrum at $E \gtrsim 10^{18.5}$ eV.

On the other hand, producing a spectrum with a steepening break similar to that observed at the cosmic ray spectrum "knee" is much harder: It demands the presence of *two* distinct acceleration mechanisms, one of which carries the particles to the "knee" with spectrum $\propto E^{-2.75}$ and a second one which takes practically *all* the particles that reach the "knee" via the first mechanism *and only these*, to a thousandfold higher energy with spectrum $\simeq E^{-3}$. If this second acceleration mechanism accelerated only a fraction of the particles that reach the "knee" (a perfectly "reasonable" assumption for most acceleration processes), it would lead to a (not observed) discontinuity in the spectrum at this energy. To complicate matters further, the most promising acceleration mechanism of galactic cosmic rays, namely supernova shocks, can barely produce (even theoretically) particles of energies as high as the energy of the "knee" [10], even with the diffusion coefficient at the Bohm value [11]. Energies as high as that can be achieved only by assuming that the cosmic ray composition at this point consists mainly of Fe nuclei. There exists no known (to the authors) mechanism which would carry even a fraction of the (diffusing through interstellar space) particles of the "knee" to the energy of the "ankle", in a way that produces the observed spectrum.

Motivated by the above considerations we are led to propose that the break at the "knee" of the cosmic ray spectrum is indicative, not of a distinct acceleration mechanism, but of the emergence of "new physics" in the high energy proton interactions, namely of a new channel beyond those considered in the models employed to infer the primary particle energy in the air shower arrays. If a fraction of the energy associated with this new channel is in a form that does not trigger these detectors, it will result to an underestimate of the primary particle's energy. For a cosmic ray spectrum which is a *single* power law in energy, this underestimate will manifest as an increase in its slope (a "knee") at the energy at which this new channel turns-on, with the spectrum reverting to its original slope when it eventually saturates. Furthermore, to account for the break observed at the "knee" of the cosmic ray spectrum, this new channel should "turn-on" at an energy $\simeq$ TeV at the center of mass, a scale tantalizingly close to that at which the emergence of "new physics" is anticipated on the basis of rather general considerations.

"New physics" scenarios appear in theoretical models which puport to extend the extremely successful Standard Model (SM) of strong and electroweak interactions to the gravitational interaction. Standing in the way of such an enterprise is the disparity between the weak ($\sim 10^2 - 10^3$ GeV) and the gravitational ($\sim 10^{19}$ GeV) scales. It is well known that, due quantum radiative corrections involving the Higgs fields, these scales cannot be much different without an incredible amount of fine tuning (this constitutes the so-called hierarchy problem).

A possibility that could remedy the situation is supersymmetry (SUSY), a symmetry that interrelates bosons and fermions [13]. In this theory the boson and fermion loop radiative corrections have opposite signs and cancel each other, thus making it possible to sustain the two vastly different scales. SUSY doubles the number of fundamental particles, since each particle must have a superpartner (sparticle). A mild spontaneous breaking of SUSY puts the masses of sparticles at the $\sim M_W$ scale. In most models a new multiplicatively conserved quantum number (R-parity) allows a heavy sparticle to only decay into a state that contains a lighter sparticle (R-parity conservation) with the lightest superparticle (LSP) escaping detection, thus providing the characteristic signature of missing energy (e.g. $p\,p \rightarrow$ gluinos which decay to the (undetected) LSP photinos)

Another way to alleviate the hierarchy problem is to replace the fundamental scalar Higgs by a composite Higgs made out of "techni-fermions" [14]. Technicolor, a new non-abelian gauge interaction, modeled on QCD, becomes strong at a scale $\Lambda_T \sim 1$ TeV. It acts between the techni-fermions, which carry also ordinary color in addition to technicolor. Thus it is suspected that in $p\,p$ collisions at $E \sim$ TeV technihadrons are produced, in particular techni-rho, which then decay to Ws (the decay $\rho_T \rightarrow WW$ is the analog of the QCD decay $\rho \rightarrow \pi\pi$). A significant fraction of the W decays involve neutrinos and therefore missing energy in the detecting array.

An altogether different way of resolving the hierarchy problem has been proposed recently [15] by postulating that the observed 4$-$dimensional universe is embedded in a higher dimensional space of D dimensions ($D = 4 + n,\ n > 1$). While the SM fields are constrained to live on the (usual) 4$-$dimensional subspace (brane), gravity can freely propagate in the $D-$dimensional space (bulk). The fundamental scale M_f of gravity in D dimensions is then smaller than the 4$-$dimensional (effective) Planck scale M_{Pl} ($M_f \ll M_{Pl}$; in fact by construction $M_f \sim$ TeV). During now a collision the produced gravitons migrate in the bulk, thus resulting in missing energy. The multiplicity of produced gravitons rises with energy and at energies close to M_f (few TeV) events with significant missing energy will be abundant.

To avoid making a specific choice from the list of available alternatives at this early stage of our investigation, we model the process simply as the production and decay of a system of total invariant mass $M_0 = 2$ TeV and we parametrize the entire process by two parameters: the fraction y of the primary particle's energy that registers in the cosmic ray detectors and the asymptotic (i.e. at energies much higher than the production threshold) ratio α of the cross section associated with this new channel to that of the standard interactions.

On dimensional grounds, the cross section of the new channel is assumed to be of the form

$$\sigma_n(\tau) = \frac{B}{s} g(\tau) \tag{1}$$

where B is a dimensionless constant (related to α), $s = 2m_pE$ and $g(\tau)$ is a function of the dimensionless ratio $\tau = M_0^2/s$. At high energies we expect the $p\,p$ interactions to be dominated by gluon scattering and accordingly

$$g(\tau) = \int_\tau^1 f(x) f(\tau/x)\, dx \tag{2}$$

where $f(x)$ is the gluon distribution within the proton, which we parametrize as

$$f(x) = \frac{1}{2}(N+1)\frac{(1-x)^N}{x}\ , \quad \text{with} \quad N\ =\ 6 \tag{3}$$

For the conventional $p\,p$ interactions the cross section rises slowly with energy and for our purposes we consider it to be a constant $\sigma_o(E) \simeq 80$ mbarn. At energies above the new physics threshold the cosmic ray interactions will proceed either through the standard channels with probability $P_o(E) = \sigma_o(E)/[\sigma_o(E) + \sigma_n(E)]$ or through the new channel with probability $P_n(E) = \sigma_n(E)/[\sigma_o(E) + \sigma_n(E)]$; given that $\tau g(\tau) \rightarrow 1/C_6 =$ constant for $\tau \rightarrow 0$, setting $B = M_0^2 C_6 \sigma_o \alpha$ we get $\sigma_n(E)/\sigma_o(E) \rightarrow \alpha$ for $E \gg M_0^2/2m_p$ as desired.

Whenever high energy cosmic ray particles interact through the new channel, events of total energy E' will register at the detector an energy $E = yE'$ $(y < 1)$. Therefore, if the cosmic ray intensity is $I(E)$, for particles interacting through this new channel, the *inferred* intensity will be of the form

$$\int I(E')P_n(E')\delta(E - yE')\,dE' = \frac{1}{y}\, I\left(\frac{E}{y}\right) P_n\left(\frac{E}{y}\right) \tag{4}$$

while for events interacting through the conventional channel the resulting intensity will have a similar form but with $y = 1$ and $P_o(E)$ in place of $P_n(E/y)$.

Assuming the incident *galactic* cosmic ray spectrum to be of the form $I_{IG}(E) = E^{-\gamma} exp(-E/E_0)$ with $\gamma \simeq 2.75$ and $E_0 \simeq 10^{18.5}$ eV, a value consistent with the earlier argument on the cosmic ray gyroradii at $E \simeq E_0$, the observed cosmic ray flux at an energy E will be

$$I_O(E) = E^{-\gamma} e^{-E/E_0} \Big[\frac{1}{1 + C_6 \alpha\, \tau g(\tau)} + \frac{\alpha\, y^{\gamma-1}\, e^{-E/yE_0 + E/E_0}}{1/[C_6(\tau y) g(\tau y)] + \alpha}\Big] \tag{5}$$

The first term in the square brackets in Eq. (5) represents the contribution to the spectrum from interactions through the conventional channels while the second that due to the new one. The presence of the exponential cut-off broadens and deepens the effects of the presence of the new channel. Their combined effect is necessary for a good fit to the data.

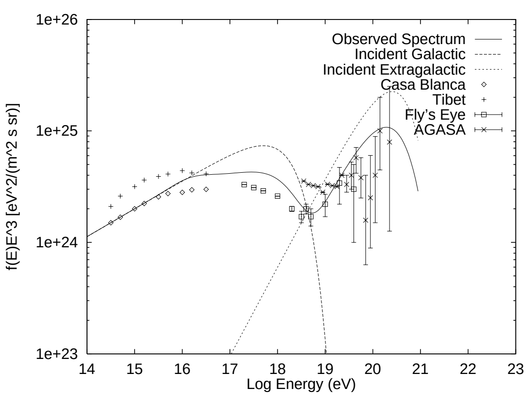

FIG. 1. The cosmic ray spectrum $f(E)$ multiplied by E^3 for $E > 10^{14}$ eV. Long and short dashed lines are respectively the incident galactic and extragalactic components. Solid line is the combined spectrum expected to be measured for $y = 1/2,\ \alpha = 2$. +'s are the Tibet data, diamonds the Casa Blanca data, squares the Fly's Eye data and $\times$'s the AGASA data.

In addition to the galactic cosmic ray component, whose contribution is expected to be unimportant beyond $E_0 \simeq 10^{18}$eV, there exists also an extragalactic component, whose reprocessing in the atmosphere should also result in a modification of its spectrum according to the prescription of Eq. (5). The precise form of this component is of course unknown since it is dominated at lower energies by the galactic component. Following [1] we assume its spectrum to be of the form $I_{EG}(E) \propto E^{-q} exp(-E/E_1)$ with $q \simeq 2.2 - 2.6$ and $E_1 \simeq 10^{20} - 10^{20.3}$ eV. In Figure 1 we present the entire (galactic + extragalactic) cosmic ray spectrum from $10^{14} - 10^{21}$ eV, with $\gamma = 2.75, q = 2.2, E_0 = 2\ 10^{18}\text{eV}, E_1 = 10^{20.3}\text{eV}$ by applying the effects of the new postulated channel in the interaction to both components with $y = 1/2,\ \alpha = 2$. We also plot the relevant data from two different experiments in each of the $10^{14} - 10^{16}$ eV (Tibet [16], CASA-BLANCA [17]) and $10^{18} - 10^{20}$ eV (Fly's Eye Stereo [2], AGASA [18]) energy ranges. We expect that these should bracket the true values of the corresponding parameters and should serve as a gauge of the systematic errors involved in computing the cosmic ray spectra in each range.

While it is very difficult to draw immediate conclusions favoring specific models from the existing data our general considerations appear to be on the correct footing: the apparent very sharp change in cosmic ray composition to almost exclusively Fe, inferred from the abrupt change in the depth of the maximum in the shower development around 10^{16} eV (fig.5 of [17]), is qualitatively of the form expected by a sharp increase in the interaction cross section, such as we propose, and the ensuing dispersion of the available energy to a large number of secondary particles.

Concentrating for the moment in the $10^{15} - 10^{17}$ eV region, this figure conveys the important message that, despite its very simple physics input, our postulate can produce a "knee" at the observed energy and of the observed change in slope in the cosmic ray spectrum. Of particular interest is the fact that this transition is quite sharp, in agreement with observations, a fact generally hard to achieve by more conventional schemes such as an energy loss mechanism. The additional assumption of a cut-off in the galactic component can then produce a good fit to the data from $\sim 10^9 - 10^{18.5}$ eV. While this latter assumption is necessary, it is also reasonable, supported both theoretically (the gyroradii arguments above) and experimentally (as discussed in [1]) by the observed increase in the cosmic ray anisotropy at this energy [19]. Considering the simplicity of the assumptions employed so far we think that this fit is particularly good. One could think of several ways for improving this fit, if necessary, at the expense of introducing more detail into the high energy physics interactions (for example a variation in the multiplicity of the new particle with energy). However, the present quality of the data does not warrant such an extension. The presence of the extragalactic component does affect the values of the fitting parameters (in particular the values of q and E_0 are closely related) since this component does contribute to the flux at lower energies. However, this fit seems to affect little the values of y and α used in fitting the spectrum at the "knee".

Where all these leave us? Our interpretation carries with it a number of consequences: (a) To start with, it implies the presence of "new" structure in the high energy physics interactions at energies consistent with those suspected on the basis of generic theoretical considerations. The new physics is slightly beyond the reach of the Fermilab Tevatron, but it will be preeminetly present at LHC. The "benchmark" signature for technicolor at LHC is the production of a pair of Ws with total invariant mass of few TeV. Supersymmetry will manifest with strong jet activity, each jet having a large mass of few hundred GeV. Low scale gravity will induce events with large missing energy. (b) On the cosmic ray physics side, our proposal makes the radical suggestion that the cosmic ray sources must, by and large, produce single power law spectra extending to the "ankle" (rather than the "knee"). This then leads to the unsettling conclusion that supernovae should not be *the* dominant contributor to the cosmic ray spectrum. It is interesting to note that independent considerations recently pointed to similar conclusions [20]. Hints to the nature of these sources may in fact be provided by the observed anisotropy at $E \sim 10^{18}$ eV toward the galactic center [19]. We plan to revisit both these issues in a future publication.

While this paper was being written, the potential effects of physics beyond the Standard Model were announced (deviation of the muon $g-2$ value from that of the standard model, hep-ex/0102332). This effect was interpreted as requiring the presence of a supersymmetric particle of mass ~ 500 GeV, similar to that involved in our considerations.

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